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Comparison of the simulated gamma-ray attenuation coefficients with the real measurements*

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The gamma-ray linear and the mass attenuation coefficients of Pb, Al, Cu, and plexiglass materials were calculated from both experimental and theoretical (simulation) methods. For the experimental results, a spectrometer, which was consisted of a NaI(Tl) inorganic scintillation detector, was used. The theoretical attenuation values were calculated by means of the FLUKA Monte Carlo (MC) and XCOM programs. Obtained attenuation coefficients from the experiment and the theoretical methods were compared with each other and literature values.

Keywords: Gamma attenuation coefficients, NaI(Tl) scintillation detector, FLUKA, XCOM

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I. INTRODUCTION

Gamma rays incident on matter interact naturally with it, resulting in absorption, scattering, transmitting, etc. These processes are called attenuation. The attenuation of the photons is determined by a coefficient, with which it defines linear and mass attenuation [1].

Monte Carlo (MC) method simulates the interaction of radiation with matter. It can be demonstrated as a black box to which we have to provide some input data. These are details of geometry of the radiation source, target and medium, type of radiation, energy and direction of radiation flight, etc. [2].

One of the MC programs is FLUKA. It is a general purpose tool for calculations of particle transport and interactions with matter, covering and extended range of applications spanning from proton and electron accelerator shielding to target design, dosimetry, detector design, etc. Interaction and propagation in matter of any particle can also be simulated by means of FLUKA [3, 4].

Data on the scattering and absorption of the photons (X-rays, gamma-rays, bremsstrahlung) are required for many scientific, engineering, and medical applications. A convenient alternative approach is to generate the cross sections and attenuation coefficients for compounds and mixtures as needed, using a personal computer. XCOM is a computer program which provides these tasks for the desired energies from 1 keV up to 100 GeV [5].

Ermis and Celiktas [6] calculated the gamma-ray linear attenuation coefficients of different materials by means of the pulse shape discrimination timing method. Beta attenuation coefficients were also investigated via the timing method by the same authors [7]. Mass attenuation coefficients of different types of inorganic scintillation materials were examined via experimental and GEANT4 MC methods by Medhat and Wang [8]. Demir *et al*. [9] investigated the mass attenuation coefficients of water, bakelite, and concrete by using the FLUKA MC method. MC code was used to determine the gamma-ray mass attenuation coefficients of some soil samples by Tarim *et al*. [10].

In the present work, the gamma-ray linear and the mass attenuation coefficients of Pb, Al, Cu, and plexiglass materials were determined by means of experimental and theoretical (simulation) methods. The calculation of the gamma-ray attenuation coefficients through the FLUKA MC program was carried out in order to check the validity of the program for the calculation of attenuation coefficients of the different absorbers. In addition, it has been observed from the results of literature browsing that limited number of studies were available on using FLUKA for the calculation of attenuation coefficients. This situation motivated the Authors to introduce this work. A spectrometer, which was consisted of a NaI(Tl) inorganic scintillation detector, was used to determine the experimental results. The theoretical attenuation coefficients were also calculated by the XCOM program to compare the results through FLUKA with those of XCOM. In FLUKA, the effect of the number of incident gamma photons on the absorbers was also investigated to determine how gamma photon numbers affect the results of the calculation of the linear and mass attenuation coefficients. Obtained results were also compared to the literature values. They showed that the linear and mass attenuation coefficients of the materials could accurately be calculated through the FLUKA program.

II. METHODS

In the experimental section of the study, the spectrometer which was consisted of a NaI(Tl) scintillation detector, was used to determine the gamma-ray attenuation coefficients of Pb, Al, Cu, and plexiglass ($C_5O_2H_8$) materials. The detector was produced by REXON Inc. (Beachwood, OH, USA). It has a 3 inch-diameter and 3 inch-thickness. A standard radioactive ^{137}Cs solid point source as a gamma emitter was used. Its activity and half-life are 5 μCi and 30.07 y, respectively [11].

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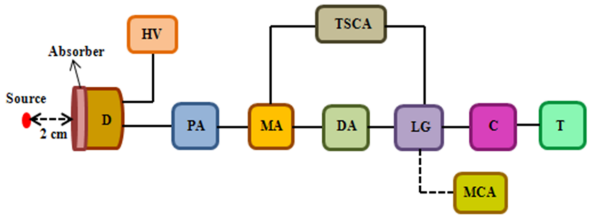

Fig. 1. (Color online) Block diagram of the used experimental spectrometer (D: Detector, HV: High voltage power supply, PA: Preamplifier, MA: Main amplifier, TSCA: Timing single channel analyzer, DA: Delay amplifier, LG: Linear gate, C: Counter, T: Timer, MCA: Multichannel analyzer).

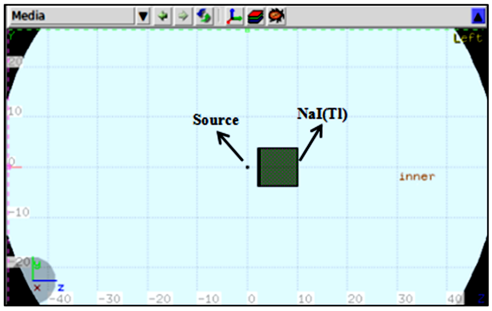

Fig. 2. (Color online) Detector and source position in FLUKA.

The experimental spectrometer is shown in Fig. 1. In the spectrometer, the detector output was sent to a preamplifier (PA, ORTEC 113). The PA output was forwarded to a main amplifier (MA, ORTEC 485) and a delay amplifier (DA, ORTEC 427A), respectively. Its output was directed to a linear gate (LG, ORTEC 426). The second parallel output from MA was sent to LG through a timing single channel analyzer (TSCA, ORTEC 553) to use only 661.6 keV-energy photons in the experiment. LG's output was finally connected to a counter (C, ORTEC 775) and a timer (T, ORTEC 719) in order to record the photons passing through the absorber materials.

The Pb, Cu, Al, and plexiglass absorber materials at various thicknesses were placed between the detector and the gamma-ray source. Their dimensions were 10 cm × 10 cm, and the thicknesses were 0.1 cm for Pb and Al, and 0.11 cm and 0.2 cm, for Cu and plexiglass, respectively. The absorber materials were placed 2 cm away from the detector surface. The count period for each absorber thickness was 100 s. Background correction was also performed to obtain net counts. These net counts were determined for each absorber thickness. According to these results, net counts (N) vs. thicknesses were plotted (attenuation graphs). The attenuation graphs were generated in a semi-logarithmic scale. Linear attenuation coefficients of the absorbers were calculated through the slope of these attenuation graphs. Mass attenuation coefficients were also determined by dividing the obtained linear attenuation coefficients by the absorber densities.

In the theoretical section of the study, the FLUKA MC simulation program (ver. 2011.2.15), which was installed on an Ubuntu (ver. 11.04) operating system, was used to determine the gamma photon numbers transmitted through the absorber materials. Afterwards, we determined the number of absorbed photons in the material to evaluate the linear and mass attenuation coefficients. After ten cycles run of each set of different materials and gamma energies, linear and mass attenuation coefficients were calculated from the resulting output files, which were analyzed by a ROOT (ver. 5.34.13) macro. The mean of the ten cycles run of each material was given as a calculation result, with the standard deviation calculated by the program. A schematic representation of the source and detector construction in the program is shown in Fig. 2.

The procedure in the theoretical section was the same as the experimental section to obtain theoretical gamma-ray mass attenuation coefficients. 661.6 keV-energy photons were used in the calculations. In these calculations, 500, 1000, 5000 and 10 000 photons were sent to each absorber material, respectively to investigate the effects of photon numbers on the attenuation coefficient calculations.

In the final section of the study, the gamma-ray mass attenuation coefficients of the absorbers were also calculated from the XCOM program (version 3.1) developed by Berger and Hubbel [3]. In the calculation, the absorber material was first chosen from its database. The gamma ray energy was then specified. Finally, the gamma-ray mass attenuation coefficient of the chosen material was calculated. In order to

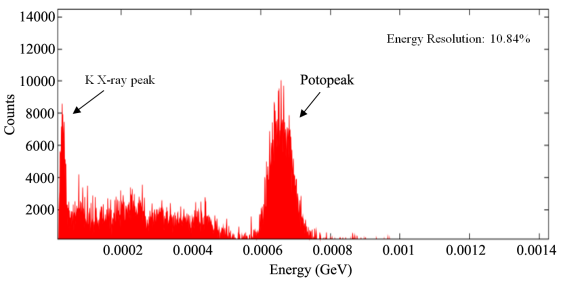

Fig. 3. (Color online) Obtained theoretical gamma energy spectrum via FLUKA program (GeV is the standard energy unit).

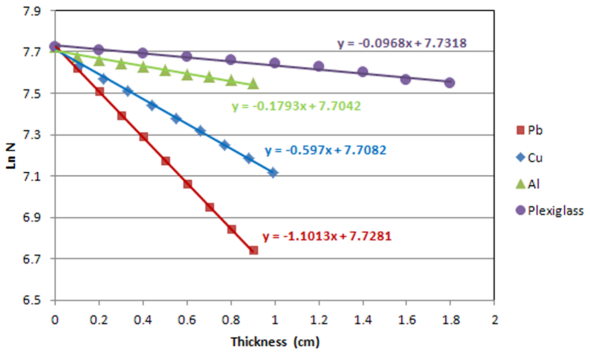

Fig. 4. (Color online) Experimental attenuation graphs for Pb, Cu, Al and plexiglass.

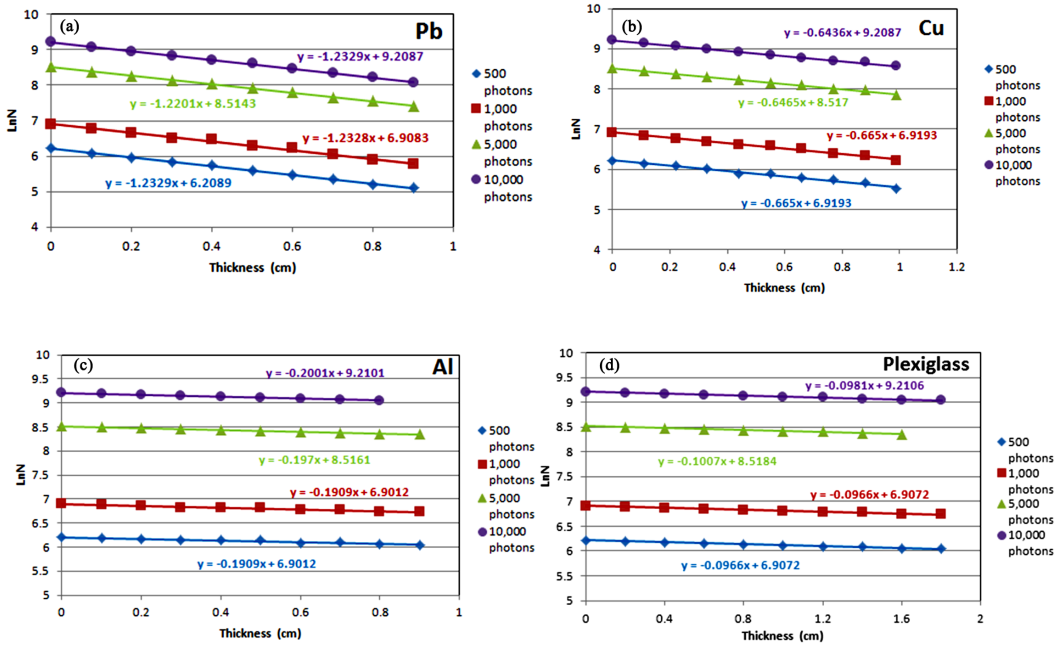

Fig. 5. (Color online) Theoretical attenuation graphs for Pb (a), Cu (b), Al (c), and plexiglass (d) at various photon numbers.

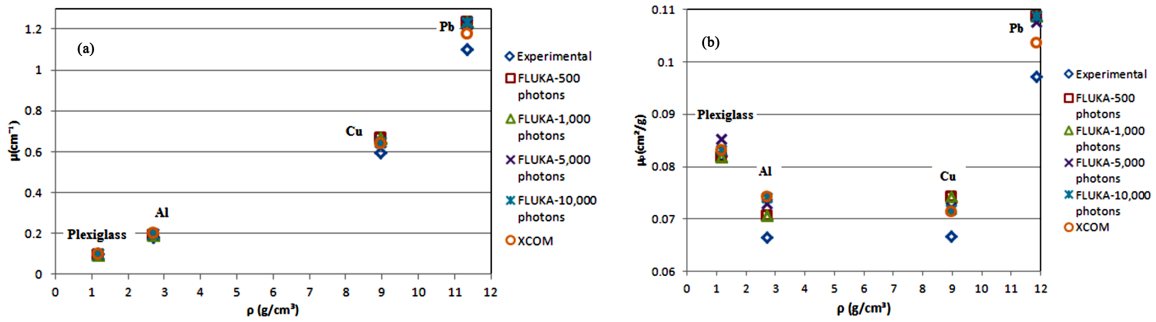

Fig. 6. (Color online) Gamma-ray linear attenuation coefficients vs. absorber densities (a) and Gamma-ray mass attenuation coefficients vs. absorber densities (b).

TABLE 1. Obtained linear and mass attenuation coefficients by means of experiment and XCOM program

Material	Linear attenuation coefficient (cm^{-1})			Mass attenuation coefficient (cm^2/g)		
	Exp.	XCOM	Literature	Exp.	XCOM	Literature
Pb	1.1013 ± 0.0056	1.1748 ± 0.0060	1.2156 [12, 13]	0.0971 ± 0.0004	0.1036 ± 0.0005	0.1072 [12, 13]
Cu	0.5970 ± 0.0027	0.6383 ± 0.0032	0.6445 [13]	0.0666 ± 0.0003	0.0712 ± 0.0004	0.0721 [13]
Al	0.1793 ± 0.0009	0.2006 ± 0.0012	0.2003 [13]	0.0664 ± 0.0002	0.0743 ± 0.0005	0.0742 [13]
Plexiglass	0.0968 ± 0.0006	0.0980 ± 0.0005	0.1026 (for 600 keV) [14]	0.0820 ± 0.0003	0.0838 ± 0.0004	0.0870 (for 600 keV) [14]

TABLE 2. Obtained linear attenuation coefficients via FLUKA MC method at various photon numbers

Material	Linear attenuation coefficient (cm^{-1})				
	FLUKA (500 photons)	FLUKA (1000 photons)	FLUKA (5000 photons)	FLUKA (10 000 photons)	Literature
Pb	1.2327 ± 0.0061	1.2281 ± 0.0057	1.2190 ± 0.0060	1.2167 ± 0.0059	1.2156 [12, 13]
Cu	0.6648 ± 0.0033	0.6612 ± 0.0032	0.6460 ± 0.0030	0.6433 ± 0.0031	0.6445 [13]
Al	0.1909 ± 0.0008	0.1925 ± 0.0011	0.1968 ± 0.0010	0.2001 ± 0.001	0.2003 [13]
Plexiglass	0.0957 ± 0.0006	0.0985 ± 0.0005	0.0998 ± 0.0008	0.0972 ± 0.0007	0.1026 (for 600 keV) [14]

TABLE 3. Obtained mass attenuation coefficients via FLUKA MC method at various photon numbers

Materia	Mass attenuation coefficient (cm^2/g)				
	FLUKA (500 photons)	FLUKA (1000 photons)	FLUKA (5000 photons)	FLUKA (10 000 photons)	Literature
Pb	0.1087 ± 0.0055	0.1083 ± 0.0053	0.1075 ± 0.0051	0.1073 ± 0.0052	0.1072 [12, 13]
Cu	0.0742 ± 0.0005	0.0738 ± 0.0004	0.0721 ± 0.0003	0.0718 ± 0.0001	0.0721 [13]
Al	0.0707 ± 0.0004	0.0713 ± 0.0005	0.0729 ± 0.0006	0.0741 ± 0.0005	0.0742 [13]
Plexiglass	0.0818 ± 0.0005	0.0842 ± 0.0007	0.0853 ± 0.0008	0.0831 ± 0.0006	0.0870 (for 600 keV) [14]

check the validity of the obtained results from the simulation program, these results were compared with the experimental, XCOM, and literature values.

III. RESULTS AND DISCUSSION

Obtained theoretical energy spectrum of the source from the FLUKA program is shown in Fig. 3. The semi-logarithmic experimental distributions of recorded counts vs. absorber thicknesses (attenuation graphs) are shown in Fig. 4.

In the FLUKA MC method, 661.6 keV-energy mono-energetic gamma photons were sent to the absorber materials. The photons transmitted through them were detected, as in the experiment. By this way, it has been performed that the method was in parallel with the experimental procedure.

The theoretical attenuation graphs of the absorber materials from the FLUKA MC method were obtained at various photon numbers to reveal the effect of the incident photon numbers on the absorber. These are shown in Fig. 5.

Obtained experimental and theoretical gamma-ray mass attenuation coefficients are shown in Tables 1–3.

In order to evaluate the behaviors of gamma-ray linear and mass attenuation coefficients with respect to the absorber densities, Fig. 6 was plotted.

In this work, gamma-ray linear and mass attenuation coefficients for Pb, Al, Cu, and plexiglass materials were determined by using three different methods in that experiment, the FLUKA MC method, and the XCOM program. In the experimental section, the attenuation coefficients were determined using a spectrometer, which consisted of a NaI(Tl) inorganic scintillation detector. The theoretical linear and mass attenuation coefficients were also designated. For these purposes, the XCOM and FLUKA programs were used.

First, the ^{137}Cs gamma energy spectrum was achieved from both experimental and FLUKA MC method. In an experimental data acquisition, the dead time is a very important parameter because it leads to pulse pile-up and spectrum distortion effects in the energy spectrum [1]. The dead time values were smaller than the threshold of 30%-40%, therefore, no pile-up and spectrum distortion effects were seen in the experimental energy spectrum [15]. This conclusion contributes to the compatibility of the presented experimental results with the theoretical ones. In this respect, the energy resolution values from the experimental and theoretical spectra were 10.88% and 10.84%, respectively. It can be noticed that these values are very close to each other.

To enhance the reliability of the results, mono-energetic gamma photons (661.6 keV) incident on the absorber materials were utilized in both the experimental and theoretical sections.

The theoretical gamma energy spectra of some radioisotopes through some MC programs, such as MARTHA, EGS4, MCNP, and GEANT4, were achieved with various studies [16–19]. In this work, the gamma-ray linear and mass attenuation coefficients were calculated by means of the FLUKA MC method, in addition to the theoretical energy spectrum of the radioisotope. Moreover, the obtained theoretical attenuation coefficients were compared one-to-one with those of the experimental and literature values in the Tables above.

The results over 1000 photons were generally closer to the literature values. This leads us to the conclusion that, due to few transmitted gamma photons through the absorbers, use of more than 1000 photons is suggested in the attenuation coefficient calculation process for more reliable results with less systematic error if the coefficients are calculated with the FLUKA MC program.

When we compared the obtained results to the literature values, it was found that all the attenuation coefficients, which were achieved by experimental and theoretical methods, were in accordance with them (Tables 1–3).

IV. CONCLUSION

The compatibility of the attenuation coefficient results from FLUKA with the experiment, XCOM calculations, and literature has been shown that the FLUKA program could be used as an alternative method in the determination of the attenuation coefficients of materials.

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